Suitability of revision to MUSLE for estimating sediment yield in the Loess Plateau of China

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Abstract This study evaluated the effect of a combination of revisions to the cover and management factor (*C*), support practice factor (*P*), and topographic factor (*LS*), and to determine the best use of each combination for modified universal soil loss equation (MUSLE) being applied in the Loess Plateau of China. Eight combinations were built based on common local methods of revision to factors *C*, *P*, and *LS* in three ways (single factor revised, two factors revised, and three factors revised, respectively). By validating the effect of these combinations on sediment yield estimation using the Nash–Sutcliffe coefficient of efficiency (NSE), normalized root-mean-square error (NRMSE), correlation coefficient (*R*), and angle between liner trend line and 1:1 line, the optimal combination was selected. Results show that: (1) the original method significantly overestimates the sediment yield; (2) when

revising a single factor, the *LS* factor revision has the greatest positive effect; (3) when revising two factors, the combination of a simultaneous revision to *C* and to *P* has the smallest angle between the liner trend line and the 1:1 line (1.37°); if the estimating accuracy of sediment peak is required, this combination may thus be a useful approach; and (4) when revising *C*, *P*, and *LS* simultaneously, the combination has the highest NSE (0.76), lowest NRMSE (1.19), and the highest correlation coefficient (0.760), and may be used to estimate sediment yield. The suitability of MUSLE is enhanced using the common local revision to factors *C*, *P*, and *LS*. Under the assumption that level terrace spatial information can obtain effectively (or that there are few level terraces), these findings can be applied to the Loess Plateau for the design of soil and water conservation measures and for flood disaster assessment, and applied to future model applications in the Loess Plateau.

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Keywords Suitability of MUSLE · Combination · Cover and management factor · Support practice factor · Topographic factor · The Loess Plateau of China

1 Introduction

The modified universal soil loss equation (MUSLE) is a runoff-sediment model of optimizing hydrological model parameters, based on runoff characteristics, and is often used to estimate the sediment yield from rainstorm events for the outlet of the watershed (ASCE 1970; Williams and Berndt 1977). By replacing the rainfall factor with a runoff factor, sediment yield prediction accuracy is increased (Williams and Berndt 1977). To date, the MUSLE has been adopted to predict sediment yield in several regions, including America

(Zhang et al. 2009; White et al. 2010), Iran (Sadeghi and Mizuyama 2007), Iraq (Mohammad et al. 2012), India (Jain et al. 2010), and China (Ouyang et al. 2010). Most of these studies have commonly revised MUSLE factors to improve its suitability for particular regions.

Estimation of rainstorm-generated sediment yield by means of a runoff-sediment model is an important way to quantitatively evaluate the effect of soil and water conservation measures and predict the risk of flooding in the Loess Plateau of China. The Loess Plateau region, located in Northern China, experiences arid and semi-arid climate conditions over an area greater than 600,000 km² (Lü et al. 2012), and shows one of the highest erosion rates worldwide (Lal 2003). Recently, significant changes in runoff and sediment discharge in the area have been reported by many studies (Liang et al. 2013). The area's runoff and sediment yield are often dominated by rainstorms during the annual flood season of June–September (Mou 1996). The consequences of soil erosion have grown to the point that conservation of agricultural soils has become a matter of food security (Gates et al. 2011). At the same time, the rate of sediment deposits in the lower reaches of the Yellow River is causing the river bed to rise and is accompanied by floods (Shi and Shao 2000), adding to the difficulty of Yellow River basin flood disaster prevention. Thus, the estimation of rainstorm-generated sediment yield based on a runoff-sediment model with a shorter time interval will be a critical tool for the design of soil and water conservation measures and for flood disaster assessment in the Loess Plateau.

MUSLE may be useful to estimate the sediment yield in the Loess Plateau. However, due to various water conservation measures, the steep and fragmented topography, and its degenerated vegetation, the dominant erosion pattern and factors in the Loess Plateau area are different from those found in other parts of the world (Qiu et al. 2012). This should make the applicability of MUSLE for sediment yield estimation limited in this region because the factors of MUSLE have remarkable regional characteristics. For these reasons, revising the factors of MUSLE for improving its suitability in the Loess Plateau is an important contribution.

There has been much focus on revising the factors of MUSLE. For instance, Cai et al. (2000) paid more attention to the effect of vegetation coverage (VC) on soil erosion, revising the cover and management factor (C). Wang and Jiao (1996) revised the support practice factor (P) based on the relationship between land utilization and water conservation measures. Liu et al. (1994), Liu et al. (2000) focused on the characteristics of the Loess Plateau's steep slope, and revised the slope gradient factor (S) and slope length factor (L). These studies undoubtedly represent positive developments for the suitability of MUSLE. However, many of them were primarily concerned with

the effect of revising a single factor on the improvement of evaluation accuracy. An additional study is required to evaluate the comprehensive effect of multi-factor revision.

The objectives of this study are as follows: first, to select common local methods of revision to the cover and management (C), support practice (P) and topographic (LS) factors of MUSLE; second, to evaluate the simulation accuracies of different combinations of revisions (i.e., original method, revised single factor, revised two factors, and revised three factors); finally, to put forward how each combination enhances MUSLE to estimate sediment yield in the Loess Plateau.

2 Materials and methods

2.1 Study area

The study area, Gushanchuan basin, is one of the most important regions in the Loess Plateau, and the Gaoshiya stream gauging station is near its outlet (Fig. 1). The basin is situated between 110°31'2"E to 111°04'57"E longitude and 39°0'3"N to 39°27'29"N latitude, covers more than 1272 km² with an elevation ranging from 795 to 1414 m above mean sea level. The basin is characterized by dramatic topographical variation between the loess hills and the gully landforms, the gully density is 2.32 km/km². More than 90 % of it is covered by loess. The average annual precipitation is 410 mm. Nearly 80 % of the precipitation is dominated by rainstorms occurring during the rainy season, from June to September. In addition,

Fig. 1 Location of the study area

approximately 75 % of the annual discharge and 99 % of the sediment yield is generated during the rainy season respectively (Wang et al. 2003).

2.2 Sediment yield modeling based on MUSLE

MUSLE is used to estimate sediment yield. This model estimates sediment yield for a given grid as a product of eight factors, whose values at a particular location can be expressed numerically and are given below (Williams 1995):

$$Sed = 11.8 \cdot (Rs \cdot q_{peak} \cdot A_{pixel})^{0.56} \cdot K \cdot C \cdot P \cdot LS \cdot CFRG \quad (1)$$

where Sed is sediment yield (t), Rs is the surface runoff volume (mm ha^{-1}), q_{peak} is the peak runoff rate ($\text{m}^3 \text{s}^{-1}$), A_{pixel} is the area of the grids (ha), K is the soil erodibility factor, C is the cover and management factor, P is the support practice factor, LS is the topographic factor, and $CFRG$ is the coarse fragment factor. Due to sediment yield is seen as a multiplier, so if one factor tends toward zero, the sediment yield will tend toward zero (Neitsch et al. 2009).

The study was carried out in four steps. For the first step we prepared the data for MUSLE, including rainfall data, soil data, remote sensing images, and digital elevation model (DEM). We then selected the estimation methods for all MUSLE factors. For the third step we compared the general accuracy of different combinations of sediment yield estimation with the effect of different combinations on sediment peak estimation. Finally, suitable revisions to MUSLE were suggested after validation. Figure 2 illustrates the proposed method with a flow chart.

2.2.1 Multipliers Rs and q_{peak} , the surface runoff volume and the peak runoff rate

The multiplier of Rs and q_{peak} , represents energy used in detaching and transporting sediment. Surface runoff can be simulated based on the distributed event flood forecasting model (Liu et al. 1965). For a given grid, by calculating the difference between precipitation and infiltration, the surface runoff can be obtained as the following equation describes:

$$Rs = P_{rec} - f \quad (2)$$

where Rs is surface runoff (mm), P_{rec} is precipitation (mm), f is infiltration (mm). Using a conceptual model, the infiltration is expressed mathematically:

$$f = F \cdot P_{rec}^r \quad (3)$$

where f is infiltration (mm); parameter F and r values can be chosen by land types, and determined by the soil

characteristics, vegetation, cover and antecedent soil moisture, etc. It is important to clarify that the distributed event flood forecasting model was developed through more than 300 artificial rainfall experiments in the Loess Plateau, and has often been applied to the Yellow River Basin in China for flood forecasting, water resources planning, and the like (Liu et al. 2008). The results of these practices indicate that the model is useful to simulate surface runoff in the Loess Plateau. Therefore, the distributed event flood forecasting model was selected to simulate the surface runoff for MUSLE.

The value of the peak runoff rate depends on the Rs . Its simulation accuracy is largely based on the simulation accuracy of the Rs . The value of the peak runoff rate is obtained from the following formula, recommended by Neitsch et al. (2009):

$$q_{peak} = \frac{\alpha_{tc} \cdot Rs \cdot A_{pixel}}{3.6 \cdot t_{conc}} \quad (4)$$

where q_{peak} is the peak runoff rate ($\text{m}^3 \text{s}^{-1}$); α_{tc} is the fraction of rainfall that occurs during the time of concentration (for short duration storms, all or most of the rain will fall during the time of concentration, so the value of α_{tc} is 1); 3.6 is a unit conversion factor; A_{pixel} is the area of the grids (ha); t_{conc} is the time of concentration for the grid.

2.2.2 K and $CFRG$, the soil erodibility factor and the coarse fragment factor

The multiplier of K and $CFRG$, reflects the effect of soil properties on erosion. Different methods and erodibility indexes have been proposed in previous studies for soils in the Loess Plateau. Jiang and Zhu (1962) related the dispersion ratio and the coefficient of expansion of soil to its resistance to scouring and detachment by flow. Jiang (1978) and Li et al. (1990) measured the relative anti-scourability indexes for loessial soils with experiments conducted in small flumes. Zhou and Wu (1993) introduced an erodibility index as the ratio of soil loss per unit runoff depth. However, the research cited so far was focused on measurable soil properties without directly relating soil erodibility indexes to measured soil loss under field conditions, moreover, due to the design criteria of plots used observe soil erodibility indexes were different, the research was very difficult to compare with each other (Zhang et al. 2001a, b; Zhang et al. 2004).

Depending on the properties of the soil itself, the values of K can be calculated using Eq. (5) suggested by Williams (1995):

Fig. 2 The whole framework for the study

$$K = \left\{ 0.2 + 0.3 \exp \left[-0.0256 S_d \left(1 - \frac{S_i}{100} \right) \right] \right\} \left(\frac{S_i}{C_i + S_i} \right)^{0.3} \left[1 - \frac{0.25 C_{or}}{C_{or} + \exp(3.72 - 2.95 C_{or})} \right] \left[1 - \frac{0.7(1 - S_d)}{1 - S_d + \exp(-5.51 + 22.9(1 - S_d))} \right] \quad (5)$$

where K is the soil erodibility factor, S_d is the percent of sand content (0.05–2.00 mm diameter particles), S_i is the percent silt content (0.002–0.05 mm diameter particles), C_i is the percent clay content (0.002 mm diameter particles), C_{or} is the percent organic carbon content of the layer (%). Equation (5) had been applied to evaluate the hydrological and erosional response of land use change in the Loess Plateau (Gao et al. 2012; Sun et al. 2014).

The $CFRG$ factor can be estimated using Eq. (6):

$$CFRG = \exp(-0.053 \cdot rock) \quad (6)$$

where $rock$ is the percent rock in the first soil layer (%).

The estimation values of factors K and $CFRG$ via Eq. (5) and (6) have been compared with other studies in

the Loess Plateau of China (Zhang et al. 2001a, b; Shi 2009). The comparison shows that the estimation values are similar to the values studied by Zhang et al. (2001a), (b) and Shi (2009) (Table 1). Thus, the estimating methods of the K and $CFRG$ factors were not revised for this study.

Among the factors of MUSLE, the estimation methods of the other factors, in addition to Rs , q_{peak} , K , and $CFRG$, including the cover and management (C), support practice (P), and topographic (LS) factors can be replaced by the common local methods. This replacement is showed in Sect. 2.3.

2.3 Revision of factors C , P , and LS

2.3.1 C , the cover and management factor

Vegetation affects the erosion capacity of surface runoff by changing the hydrodynamic characteristics of surface runoff. VC can reflect the degree of vegetation cover over land area. With increasing VC , the amount of sediment in runoff is reduced (Hofmann and Ries 1991). As long as the VC is

Table 1 Comparison of estimated K , $CFRG$ factors values and previous achievements on them

Soil textural type	Soil textural type	Estimated K	Estimated $CFRG$	Multiplier of estimated K and $CFRG$	Range of K	Observed K
Clay	Red clay	0.326	0.995	0.324	0.150–0.423	–
Loam	Chestnut soil	0.357	0.996	0.356	0.006–0.389	–
Loamy sand	Alluvial soils	0.349	0.995	0.347	0.004–0.401	–
Sandy loam	Loessal soil	0.343	0.997	0.342	0.029–0.440	0.3–0.4
Sand	Aeolian sandy soil	0.211	0.998	0.211	0.001–0.343	–

Soil textural type (U.S. Department of Agriculture)

Soil textural type (Chinese Soil Database at the Scale of 1:1 M)

Range of K values considering the gravel content calculated by (Shi 2009)

K value observed in July and August in Ansai, Shannxi province by Zhang et al. (2001a, b)

large enough, soil erosion can be controlled whether or not the vegetation is tall forest or low shrub (Jiao and Wang 2001). In order to fully reflect the effect of VC on sediment generation, the cover and management factor (C) is estimated by replacing the method proposed by Wischmeier and Smith (1978) with the formula suggested by Cai et al. (2000).

The C factor proposed by Wischmeier and Smith (1978) is expressed as the Eq. (7):

$$C = \exp([\ln(0.8) - \ln(C_{mm})] \cdot \exp[-0.0115 \cdot rsd_{surf}] + \ln[C_{mm}]) \quad (7)$$

where C_{mm} is the minimum value for the cover and management factor for the land cover, and rsd_{surf} is the amount of residue on the soil surface (kg/ha).

The revised C factor suggested by Cai et al. (2000) is expressed as the Eq. (8):

$$C = \begin{cases} 1, & c_v = 0 \\ 0.6508 - 0.3436 \lg c_v, & 0 < c_v \leq 78.3\% \\ 0, & c_v > 78.3\% \end{cases} \quad (8)$$

where C is the cover and management factor, its value is from 0 to 1. The lower the C value, the more effective the cover and management is deemed to be at reducing soil erosion. c_v is vegetation coverage of growing season, or average monthly, quarterly and annual VC (%). This method had been used to assess the soil erosion control service of ecosystems change (Fu et al. 2011) and the relationship between landscape pattern change and soil erosion (Zhang et al. 2011) in the Loess Plateau.

2.3.2 P , the support practice factor

In the Loess Plateau, support practice and land use types are closely related. The design of support practice is always dependent on the land use type and is different from that of other regions of the world. Thus, by replacing the method proposed by Wischmeier and Smith

Table 2 P factor values for contour-farmed terraced fields (Wischmeier and Smith 1978)

Land slope (%)	1–2	3–8	9–12	13–16	17–20	21–25
Contour P factor	0.6	0.5	0.6	0.7	0.8	0.9
Stripcrop P factor	0.3	0.25	0.3	0.35	0.4	0.45

(1978) (Table 2), the support practice factor (P) is assigned to different land use classes, referencing the research findings applied in the Loess Plateau of China by Wang and Jiao (1996) (Table 3). If there are no support practices, the P value is 1. The lower the P value, the more effective the conservation practice is deemed to be at reducing soil erosion.

2.3.3 LS , the topographic factor

The topographic factor (LS) was obtained by multiplying the slope length factor (L) and slope gradient factor (S). Considering the large area of Loess Plateau is covered by fragmented topography, and the proportion of steep slope is larger than that in other regions, using the research achievements in the Loess Plateau by Liu et al. (1994, 2000), the L factor and the S factor were revised, respectively.

According to the study of Wischmeier and Smith (1978), the LS factor was calculated as follows:

$$L = (L_{slp}/22.1)^m (65.4 \sin^2 \beta + 4.56 \sin \beta + 0.065) \quad (9)$$

where L_{slp} is the slope length (m), m is the exponential term, and β is the angle of the slope. The exponential term, m , was calculated:

$$m = 0.6 \cdot (1 - \exp[-35.835 \cdot slp]) \quad (10)$$

where slp is the slope of the grid expressed as rise over run (m/m).

Table 3 *P* factor values for different land use classes in Loess Plateau (Wang and Jiao 1996)

Land use	<i>P</i> value	Land use	<i>P</i> value	Land use	<i>P</i> value
Crop land ($\theta < 6^\circ$)	0.01	Open woodland	1.00	Water area	1.00
Crop land ($6 \leq \theta < 25^\circ$)	0.03	Spinney	1.00	Developed land	1.00
Crop land ($\theta \geq 25^\circ$)	0.30	Forest	1.00	Other land	1.00
Immature forest land and orchard	0.20	Grassland	1.00		

θ is the slope of crop land in degrees

Table 4 Combination of revision of factors

Combination forms	Estimation methods of MUSLE factors						
	<i>Rs</i>	q_{peak}	<i>K</i>	<i>CFRG</i>	<i>C</i>	<i>P</i>	<i>LS</i>
Single factor revised							
(a) Original method	Eqs. (2) and (3)	Eq. (4)	Eq. (5)	Eq. (6)	Eq. (7)	Table 1	Eqs. (9) and (10)
(b) Revised <i>C</i> factor					Eq. (8)	Table 1	Eqs. (9) and (10)
(c) Revised <i>P</i> factor					Eq. (7)	Table 2	Eqs. (9) and (10)
(d) Revised <i>LS</i> factor					Eq. (7)	Table 1	Eqs. (11) and (12)
Two factors revised							
(e) Revised <i>C</i> and <i>P</i> factors					Eq. (8)	Table 2	Eqs. (9) and (10)
(f) Revised <i>C</i> and <i>LS</i> factors					Eq. (8)	Table 1	Eqs. (11) and (12)
(g) Revised <i>P</i> and <i>LS</i> factors					Eq. (7)	Table 2	Eqs. (11) and (12)
Three factors revised							
(h) Revised <i>C</i> , <i>P</i> , and <i>LS</i> factors					Eq. (8)	Table 2	Eqs. (11) and (12)

The revised *L* factor was calculated as follows (Liu et al. 2000):

$$L = (L_{slp}/22.1)^{0.44} \quad (11)$$

where *L* is the slope length factor, L_{slp} is slope length in meters and 0.44 is the dimensionless exponent.

The revised *S* factor was derived from three groups as follows (Liu et al. 1994; McCool et al. 1987 a):

$$S = \begin{cases} 10.8 \sin \theta + 0.03, & \theta < 5^\circ \\ 16.8 \sin \theta - 0.5, & 5^\circ \leq \theta < 10^\circ \\ 21.9 \sin \theta - 0.96, & \theta > 10^\circ \end{cases} \quad (12)$$

where *S* is the slope gradient factor and is the slope angle in degrees.

2.4 Combination of revisions to MUSLE factors

Based on the same estimation methods of *Rs*, q_{peak} , *K*, and *CFRG* factors, by revising the estimation methods of *C*, *P*, and *LS* factors in three ways (single factor revised, two factors revised, and three factors revised, respectively), there are eight combinations including (a) the original method, (b) the revised *C* factor, (c) the revised *P* factor, (d) the revised *LS* factor, (e) the revised *C* and *P* factors, (f) the revised *C* and *LS* factors, (g) the revised

P and *LS* factors, and (h) the revised *C*, *P*, and *LS* factors, which were used to estimate sediment yield (Table 4).

2.5 Data preparation

As mentioned above, the necessary spatial data inputs for MUSLE are: hourly precipitation, DEM data, soil data, land use data, and *VC* data. Land use and *VC* data from 1989, 1998, and 2006 were used to represent data for the 1980s, 1990s, and 2000s, respectively.

2.5.1 Remote sensing data sources

In the study area, most of the sediment yield is generated during the rainy season, especially July and August, and the rainy season also yields the most crop growth and thus the most *VC*. For this reason, we acquired images during the rainy season to develop the land use and the *VC* maps. We collected three time series of satellite imagery with a resolution of 30 m: 3 August 1989 (Landsat TM 126/32), 2 July 1998 (Landsat TM 127/32), 24 July 2006 (Landsat TM 127/33). Moreover, we used global digital elevation model (GDEM) data at a resolution of 30 m to extract the topographic information needed for MUSLE, such as the slope length and slope gradient.

2.5.2 Precipitation and hydrological data

Hourly rainfall data was collected from 14 rain-gauge stations (Fig. 1). We collected 100 h of precipitation data, from August 3 to August 7, 1988 to calibrate the model, and 30 precipitation events (five from the 1980s, nineteen from the 1990s, and six from the 2000s) were used for validation. To interpolate the rainfall data, we used the inverse distance weighted (IDW) method, and we obtained observed discharge and sediment concentration data from Gaoshiya stream gauging station for calibration and validation. Hourly sediment yield was thus calculated by multiplying hourly discharge with sediment concentration.

2.5.3 Soil properties

We obtained the soil properties needed for computing soil erodibility and coarse fragment factors from the Chinese national 1:1000,000 scale soil map and the U.S. Department of Agriculture (USDA) classification system for soil texture classes. Under the USDA classification system, the soil in the Gushanchuan basin can be classified in five ways: clay, loam, loamy sand, sandy loam, and sand

Fig. 3 Soil textural map of Gushanchuan basin

Table 5 Soil texture in the Gushanchuan basin

Soil textural type (USDA)	Area (km ²)	Proportion (%)	Sand (%)	Silt (%)	Clay (%)	Organic carbon (%)	Rock (%)
Clay	0.37	0.03	23	29	48	1.17	10
Loam	478.00	37.58	29	45	26	1.42	8
Loamy sand	116.78	9.18	79	15	6	0.41	10
Sandy loam	626.43	49.25	76	12	12	0.36	5
Sand	50.42	3.96	89	6	5	0.50	2

(Fig. 3). The soil types and relevant properties are listed in Table 5.

2.5.4 Land use classification and accuracy assessment

According to the land use/cover categories suggested by the Chinese Academy of Sciences and the Chinese national system adopted in 2007 by the Chinese Land Resources Ministry, a man–machine interaction method was employed to extract the land use information, and the land use type was divided into 11 classes based on GDEM data and three time series of Landsat TM imagery. The land use types in the study area were classified as: crop land ($\theta < 6^\circ$), crop land ($6 \leq \theta < 25^\circ$), crop land ($\theta \geq 25^\circ$), immature forest land and orchard, open woodland, spinney, forest, grassland, water area, developed land, and other land (Fig. 4; Table 6).

We assessed the accuracy of the land use data interpretation with three field verifications. For the 2006 land use data interpretation, we assessed accuracy by visual verification. The results confirmed that 51 out of 57 points were correctly interpreted in 2006, with an accuracy of 89.47 %. For the 1998 and 1989 land use data, we used multiple sources of information and multidisciplinary expertise to assess the interpretation accuracy, including referencing historical documents and maps and interviewing local elder residents. The results showed that 46 out of 57 points were correctly interpreted in 1998, with an accuracy of 80.7 %, and 42 out of 57 points were correctly interpreted in 1989, with an accuracy of 73.68 %.

2.5.5 Vegetation coverage extracting

VC was calculated using *NDVI* derived from Landsat TM images:

$$\begin{cases} VC = (NDVI - NDVI_{soil}) / (NDVI_{veg} - NDVI_{soil}) \\ NDVI = (NIR - IR) / (NIR + IR) \end{cases} \quad (13)$$

where *VC* is vegetation coverage (%), *NDVI_{soil}* is *NDVI* of bare soil, *NDVI_{veg}* refers to the *NDVI* regional maximum, *NIR* is the near infrared band, and *IR* is the infrared band.

Fig. 4 Land use map of Gushanchuan basin

Table 6 Land use in the Gushanchuan basin

Land use type	Description	1989		1998		2006	
		km ²	%	km ²	%	km ²	%
Crop land ($\theta < 6^\circ$)	Cultivated land for agriculture on a slope less than 6°	58.68	4.61	53.82	4.23	53.82	4.23
Crop land ($6 \leq \theta < 25^\circ$)	Cultivated land for agriculture on a 6° – 25° slope	346.26	27.22	327.47	25.74	314.35	24.71
Crop land ($\theta \geq 25^\circ$)	Cultivated land for agriculture on a slope greater than 25°	4.73	0.37	2.95	0.23	0.00	0.00
Immature forest land and orchard	Lands dominated by immature trees	9.94	0.78	11.84	0.93	11.31	0.89
Open woodland	Lands dominated by trees with a canopy cover of 10–20 %	18.51	1.46	46.44	3.65	69.26	5.44
Spinney	Lands with woody vegetation less than 2 meters	14.22	1.12	12.24	0.96	21.38	1.68
Forest	Lands dominated by trees with a canopy cover over 20 %	0.00	0.00	2.11	0.17	2.79	0.22
Grassland	Lands with herbaceous types with a canopy cover over 5 %	798.8	62.80	788.99	62.03	759.26	59.69
Water area	Lakes, reservoirs, and rivers.	9.15	0.72	13	1.02	13	1.02
Developed land	Land covered by buildings and other man-made structures	10.05	0.79	11.48	0.90	25.9	2.04
Other land	Land with exposed soil and stone with a vegetated cover of less than 5 %	1.66	0.13	1.66	0.13	0.93	0.07

Fig. 5 Vegetation coverage map of Gushanchuan basin

Table 7 Vegetation coverage in the Gushanchuan basin

Vegetation coverage (%)	1989		1998		2006	
	km ²	%	km ²	%	km ²	%
0–10	668.00	52.52	409.83	32.22	405.99	31.92
10–20	307.30	24.16	29.41	2.31	1.26	0.10
20–30	194.46	15.29	299.80	23.57	5.06	0.40
30–40	68.50	5.39	332.55	26.14	19.98	1.57
40–50	22.49	1.77	129.70	10.20	125.92	9.90
50–60	6.97	0.55	47.75	3.75	346.73	27.26
60–70	2.59	0.20	16.09	1.26	266.19	20.93
70–80	1.04	0.08	5.00	0.39	83.58	6.57
80–90	0.41	0.03	1.41	0.11	14.50	1.14
90–100	0.26	0.02	0.47	0.04	2.77	0.22

The values of VC were calculated with a range from 0 to 100 % (Fig. 5; Table 7).

2.6 Model performance evaluation criteria

Three common statistical criteria were used to measure the agreement between estimated and observed values of runoff and sediment yield. A good agreement indicates a good model performance, and vice versa.

$$NSE = 1 - \frac{\sum_{i=1}^N (O_i - E_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} \quad (14)$$

$$NRMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (O_i - E_i)^2} / \bar{O} \quad (15)$$

$$R = \frac{\left(\sum_{i=1}^N (O_i - \bar{O})(E_i - \bar{E}) \right)}{\left(\sqrt{\frac{1}{N} \sum_{i=1}^N (O_i - \bar{O})^2} \sqrt{\frac{1}{N} \sum_{i=1}^N (E_i - \bar{E})^2} \right)} \quad (16)$$

where NSE is the Nash–Sutcliffe coefficient of efficiency (Nash and Sutcliffe 1970), NRMSE is the normalized root-mean-square error, R is the Pearson product-moment correlation coefficient, O_i is observed runoff or sediment yield, E_i is estimated runoff or sediment yield, $\bar{O}$ is the average observed runoff or sediment, N is the total number of records for comparison and $\bar{E}$ is the average estimated runoff or sediment. $NSE = 1$ represents the best model performance, and decreasing values indicate poor agreement between observed and estimated values. A lower NRMSE value indicates better model performance. A higher R value indicates better model performance.

Furthermore, in order to evaluate model performance on sediment peak estimation, a scatter plot was drawn to show the linear relationship between observed and simulated

values. The angle between the linear trend line and the 1:1 line of the scatter plot was used to indicate the model performance on sediment peak estimation. A smaller angle indicates a better model performance. Meanwhile, if the linear trend line is located above the 1:1 line then the sediment peak is overestimated, and vice versa.

3 Results and discussion

3.1 Estimation results of surface runoff

The accuracy of the sediment yield estimation is highly dependent on the hydrological results, particularly when the surface runoff is treated as an independent factor in both the soil erosion stage and the sediment transport stage (Wang et al. 2012). The estimated cumulative discharge at the outlet of the basin was compared with the observed data to evaluate the accuracy of surface runoff simulation (Fig. 6). As shown in Fig. 6, the estimated discharge matches the observed values well ($R^2 = 0.851$), and the NSE and the NRMSE values are 0.85 and 0.77,

Fig. 6 Comparison between estimated and observed discharge

Table 8 Comparison between estimated and observed sediment yield modulus for different combinations

Combination	Sediment yield modulus (t km ⁻² h ⁻¹)		Deviation (%)
	Observed	Estimated	
Single factor revised			
(a) Original method	216	524	142.59
(b) Revised <i>C</i> factor		428	98.15
(c) Revised <i>P</i> factor		415	92.13
(d) Revised <i>LS</i> factor		363	68.06
Two factors revised			
(e) Revised <i>C</i> and <i>P</i> factors		325	50.46
(f) Revised <i>C</i> and <i>LS</i> factors		290	34.26
Three factors revised			
(g) Revised <i>P</i> and <i>LS</i> factors		281	30.09
(h) Revised <i>C</i> , <i>P</i> and <i>LS</i> factors		220	1.85

respectively. The result shows that the estimated surface runoff can be used as an input for MUSLE to predict the sediment yield of the study area.

3.2 Estimation results of sediment yield

Because of the availability of input data, sediment yield was simulated at a one-hour time step. Syncing with runoff, sediment yield generation in every grid was routed to the outlet. The estimated and observed sediment yield modulus for different combinations is compared and shown in Table 8. The result shows that the original method significantly overestimates the sediment yield with a deviation of 142.59 %. By revising the estimated methods of factors *C*, *P*, and *LS*, the estimating results were increasingly satisfactory. When a single factor is revised, the deviation drops from 98.15 to 68.06 %. In the cases when two factors are revised, the deviation also drops, from 50.46 to 30.09 %. When *C*, *P*, and *LS* factors are revised simultaneously, the minimum deviation is obtained with a value of 1.85 %.

3.3 General accuracy of different combinations on sediment yield estimation

The sediment yield of tributaries is a key factor for Yellow River basin planning. General accuracy verification is an important measure to evaluate the suitability of MUSLE for estimating sediment yield of rainfall events (Fig. 7a–h; Table 9).

First, no matter how many factors of *C*, *P*, and *LS* get revised, the correlation coefficient has no obvious change, with R^2 values ranging from 0.746 to 0.760. This result indicates that the correlation between simulated and observed values is not influenced remarkably by the revision.

Second, when revising the *C*, *P*, and *LS*, respectively, the effect of the *LS* factor revision on the estimating

accuracy is the best of all (Fig. 6b–d). The NSE value of the combination (d) is 0.46. Accordingly, the NSE values in combinations (b) and (c) are 0.06 and 0.13, respectively. The NSE value of the combination (d) is 0.40, 0.33 higher than the combinations (b) and (c). This result indicates that if only one factor can be revised when there are limited data, the *LS* factor ought to have a priority to the extent possible.

Finally, the more factors get revised, the better general accuracy of MUSLE performance. In the cases where a single factor is revised, the NSE values of the combinations (b) (Fig. 6b), (c) (Fig. 6c), and (d) (Fig. 6d) are 0.06, 0.13, and 0.46, which are 0.96, 1.03, and 1.36 higher than the original method, respectively. In the cases in which two factors are revised, the NSE values of the combinations (e) (Fig. 6e), (f) (Fig. 6f), and (g) (Fig. 6g) are 0.56, 0.70, and 0.72, which are 1.46, 1.60, and 1.62 higher than the original method, respectively. When the *C*, *P*, and *LS* factors are revised simultaneously (Fig. 6h), the NSE value is 0.76, which is 1.66 higher than the original method. At the same time, it is also true that the NRMSE value declines by revising the *C*, *P*, and *LS* factors. This result indicates that the general accuracy of the combination (h) is best, and is useful to estimate sediment yield of rainfall event.

3.4 Effect of different combinations on sediment peak estimation

Accurate estimation of sediment peak is useful for flood disaster assessment. The angle between the linear trend line and the 1:1 line of a scatter plot was used to reflect the effect of sediment peak estimation in Fig. 8 a–h.

First, Fig. 8a–d clearly show that all trend lines are located above the 1:1 lines, and the angles between linear trend and 1:1 lines are 15.13°, 8.97°, 8.19°, and 4.31°, respectively. This result indicates that although all of the

Fig. 7 Comparison between estimated and observed sediment yield

four combinations including the combinations (a), (b), (c), and (d) significantly overestimate the sediment peak, the overestimation is diminishing.

Second, from Fig. 8e, it can be seen that the estimated sediment peak of the combination (e) is consistent with the observed value, having a trend line close to the 1:1 line,

Table 9 Values of model performance evaluation criteria for different combinations

Combination	NSE	NRMSE	R ²
Single factor revised			
(a) Original method	−0.90	3.32	0.752
(b) Revised <i>C</i> factor	0.06	2.34	0.748
(c) Revised <i>P</i> factor	0.13	2.24	0.746
(d) Revised <i>LS</i> factor	0.46	1.76	0.759
Two factors revised			
(e) Revised <i>C</i> and <i>P</i> factors	0.56	1.56	0.747
(f) Revised <i>C</i> and <i>LS</i> factors	0.70	1.31	0.759
Three factors revised			
(g) Revised <i>P</i> and <i>LS</i> factors	0.72	1.28	0.760
(h) Revised <i>C</i> , <i>P</i> and <i>LS</i> factors	0.76	1.19	0.760

and the better performance of the combination is supported by a smaller angle, which is 1.37°. This result shows that the sediment peak can be better estimated based on the combination (e).

Finally, as shown in Figs. 8f–h, the trend lines of combinations (f) and (h) are located under the 1:1 lines, with angles of 2.23° and 9.78°, respectively. This result indicates that the three models significantly underestimate the sediment peak and may not be appropriate for simulating the sediment peak.

3.5 Suitability of revision to MUSLE

The suitability of MUSLE is closely related to the combination method used for its factor evaluation. From Sects. 3.3 and 3.4, we inferred that the combination (h) can be used to estimate sediment yield and the combination (e) can be used to estimate sediment peak, respectively. Thirty events (five in the 1980s, nineteen in the 1990s and six in the 2000s) were used to validate this inference. Table 10 and Fig. 9 compare estimated sediment yield based on combination (h) with estimated sediment peak based on combination (e) for 30 validation events of observed data and lists the relevant deviations.

For the sediment yield estimations based on the combination (h), the deviations of five events in the 1980s range between −47.22 and 34.39 %, the deviations of nineteen events in the 1990s range between −53.54 and 47.96 %, and the deviations of six events in the 2000s range between −58.58 and 382.68 %. The estimated sediment yields of 30 validation events are plotted against the observations in Fig. 8a, and the trend line shows a statistical fit of $R^2 = 0.81$.

For the sediment peak estimations based on the combination (e), the deviations of five events in the 1980s range between −43.42 and 34.89 %, the deviations of

nineteen events in the 1990s range between −51.78 and 48.55 %, and the deviations of six events in the 2000s range between −63.75 and 2127.39 %. The estimated sediment peaks of 30 validation events are plotted against the observations in Fig. 8b, and the trend line shows a statistical fit of $R^2 = 0.90$.

Bingner et al. (1989) posited that if the underestimation or overestimation of soil erosion was within 20 % of the observed values, the simulation could be considered acceptable. For the 30 validation events, Table 10 shows that the average deviations of sediment yield and sediment peak estimations are −0.96 and 0.11 % for the 1980s, −13.02 and −10.08 % for the 1990s, and 111.93 and 361.45 % for the 2000s, respectively; this shows that the average sediment yield and sediment peak estimations in the 1980s and 1990s are within acceptable levels. Table 11 shows the respective percentages of deviation less than 20 % for sediment yield and sediment peak estimations for the three decades: 60 and 60 % in the 1980s, 36.84 and 42.11 % in the 1990s, 33.33 and 16.67 % in the 2000s. The results indicate that combination (h) and combination (e) produce reasonable estimations of sediment yield and sediment peak in the 1980s and 1990s, and give significant over-estimations of sediment yield and sediment peak in the 2000s.

The difficulty of extracting the level terrace using Landsat TM data at a resolution of 30 m is the major cause of sediment yield and sediment peak overestimation in the 2000s. In the Loess Plateau, land terracing has been an important measure for soil and water conservation since the Grain to Green Program (GTGP) launched in 1999 (Lu et al. 2009). According to local government statistical data, few level terraces were distributed in the study area before 1998; between 2000 and 2012, about 38 km² (2.98 % of study area) of man-made level terrace was built on the most severely eroded slope farmlands to decrease soil erosion and improve agricultural productivity. Level terraces can not only reduce more than 95 % of the sediment yield (Jiao et al. 1999), but they also intercept the sediment yield from the upper regions (Liu et al. 2014). Most of the level terraces are built on the hill-slopes of more than 6 ° and their surface widths are usually narrower than 15 m (Fig. 10), and are difficult to identify using the 30 m resolution remote sensing images. Due to the lack of spatial information for level terrace distribution, the result for the estimated support practice factor (*P*) value is greater than the actual value, thus significantly overestimating sediment yield and sediment peak for the 2000s.

We therefore suggest that when accurate level terrace spatial information can be obtained or when there are few level terraces, combination (h) is a more accurate method for estimating sediment yield. Furthermore, combination

Fig. 8 Effect of different factor's revision on sediment peak estimation

Table 10 Observed and estimated sediment yield and sediment peak for 30 validation events based on combination (h) and combination (e), respectively

Times	Date (Year/month/day)	Observed and estimated sediment yields based on the combination (h)				Observed and estimated sediment peaks based on the combination (e)			
		Observed (10 ⁴ t)	Estimated (10 ⁴ t)	Deviation (%)	Average deviation (%)	Observed (10 ⁴ t)	Estimated (10 ⁴ t)	Deviation (%)	Average deviation (%)
1980s	1985/07/09	176.32	154.49	12.38	−0.96	68.61	38.82	−43.42	0.11
	1985/08/04	178.51	159.36	10.73		83.99	74.88	−10.84	
	1986/08/06	93.53	79.43	−15.07		34.90	40.28	15.41	
	1989/07/22	432.67	228.37	−47.22		150.54	98.02	34.89	
	1989/07/24	292.97	393.73	34.39		83.66	87.44	4.51	
1990s	1992/07/29	460.79	439.93	−4.53	−13.02	70.89	65.19	−8.47	−10.08
	1990/08/01	54.51	29.12	−46.58		13.08	15.69	19.95	
	1992/07/25	245.58	363.36	47.96		95.07	96.39	1.39	
	1992/07/27	379.10	213.16	−43.77		81.10	78.52	−3.19	
	1992/08/05	51.41	47.48	−7.65		16.36	10.73	−34.41	
	1992/08/11	609.65	766.60	25.74		285.69	251.38	−12.01	
	1993/07/08	82.88	102.16	23.26		36.69	52.59	43.34	
	1994/07/07	1013.66	868.41	−14.33		290.85	203.24	−30.12	
	1994/07/26	276.26	128.35	−53.54		81.52	50.90	−37.56	
	1994/08/04	108.72	56.90	−47.66		56.65	29.15	48.55	
	1994/08/10	99.97	96.40	−3.57		41.47	38.55	−7.04	
	1994/08/14	104.11	53.56	−48.56		14.52	7.01	−51.78	
	1995/08/12	47.96	27.13	−43.44		9.92	8.49	−14.40	
	1996/07/16	177.85	152.21	14.42		58.07	39.89	−31.31	
	1996/08/11	690.34	566.25	−17.98		109.76	130.53	18.92	
2000s	1997/07/30	383.37	357.37	−6.78	111.93	173.54	132.41	−23.70	361.45
	1997/08/01	219.88	324.03	47.37		90.29	113.55	25.76	
	1998/07/13	292.55	197.67	−32.43		111.46	56.49	−49.32	
	1998/07/18	61.38	39.76	−35.22		20.34	10.95	−46.18	
	2000/08/16	78.95	32.70	−58.58		36.40	13.20	−63.75	
	2001/07/25	220.35	247.50	12.32		89.94	48.52	−46.05	
	2002/07/20	63.43	56.63	−10.73		10.08	14.92	48.06	
	2003/07/08	18.18	69.21	280.72		11.08	22.15	99.80	
	2003/07/30	651.20	1074.76	65.14		267.27	275.87	3.22	
	2009/09/24	10.31	49.74	382.68		0.82	18.26	2127.39	

Fig. 9 Comparison of the observed and estimated sediment yield and sediment peak for the 30 events **a** sediment yield **b** sediment peak

Table 11 Percentage of deviation less than 20 % of sediment yield and sediment peak estimations for 30 validation events

Times	Events amount	Deviation less than 20 % (sediment yield estimation)		Deviation less than 20 % (sediment peak estimation)	
		Amount	Percentage (%)	Amount	Percentage (%)
1980s	5	3	60.00	3	60.00
1990s	19	7	36.84	8	42.11
2000s	6	2	33.33	1	16.67

Fig. 10 The level terraces

(e) can be used when estimating accuracy of sediment peak is needed, as it better describes the sediment peak.

4 Conclusions

In this study, we examined the effects of revisions to cover and management(*C*), support practice (*P*), and topographic (*LS*) factors for MUSLE on sediment yield estimation in the Loess Plateau. The MUSLE performance improved at different levels, based on the combination of these factors in three ways (single factor revised, two factors revised and three factors revised, respectively). The effects differed in different revision combinations to the MUSLE factors. The original method significantly overestimates the sediment yield. When revising a single factor, the *LS* factor revision has the greatest positive effect. When revising two factors, the combination of a simultaneous revision to *C* and to *P* has the smallest angle between the liner trend line and the 1:1 line (1.37°); if the estimating accuracy of sediment peak is required, this combination may thus be a useful approach. When revising *C*, *P*, and *LS* simultaneously, the combination has the highest NSE (0.76), lowest NRMSE (1.19), and the highest correlation coefficient (0.760), and may be used to estimate sediment yield. Furthermore, the suitability of MUSLE is enhanced using the common local revision to factors *C*, *P*, and *LS*. Under

the assumption that level terrace spatial information can obtain effectively (or that there are few level terraces), these findings can be applied to the Loess Plateau for the design of soil and water conservation measures and for flood disaster assessment, and applied to future model applications in the Loess Plateau.

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